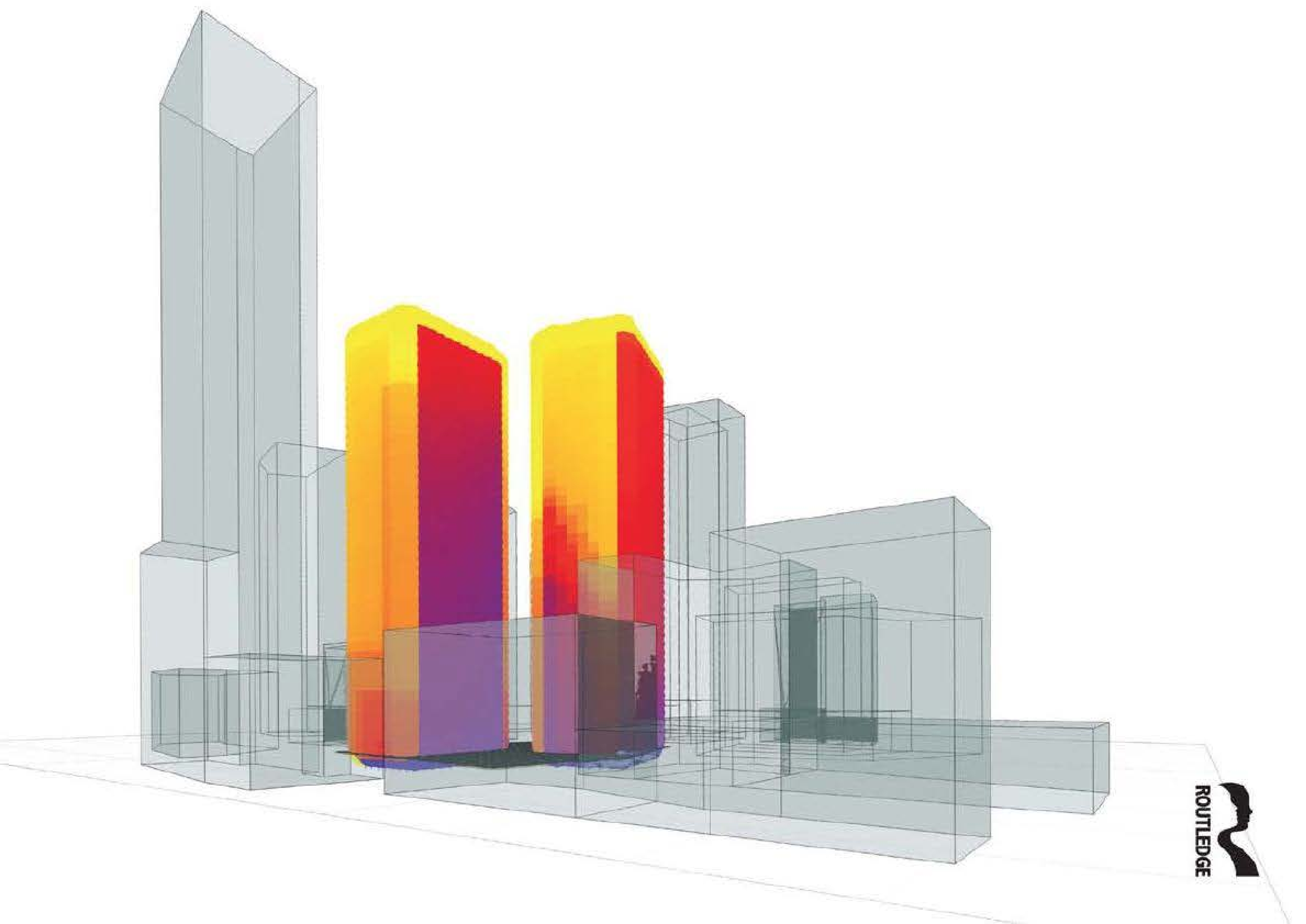
Kjell Anderson

DESIGN ENERGY SIMULATION FOR ARCHITECTS

GUIDE TO 3D GRAPHICS



ROUTLEDGE

3

Comfort and Controls

Man is the measure of all things.

—Protagoras

A shift is required from conceptualizing the occupant as a passive recipient of a set of indoor conditions, to the inhabitant, who may play a more active role in the maintenance and performance of their building.

—Cole and Brown, 2009

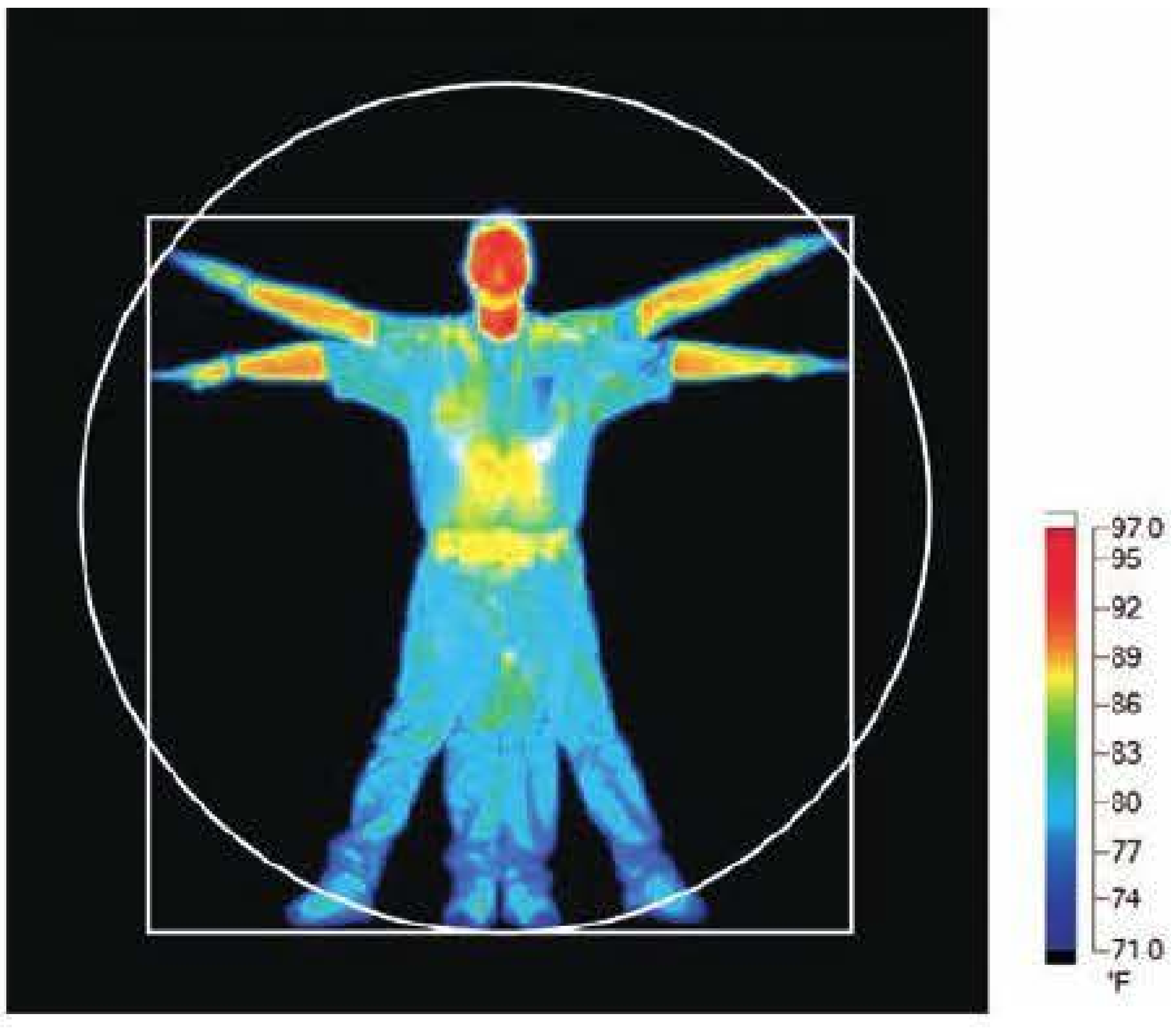
Buildings use a great deal of energy to provide comfortable environments for their occupants. We prefer certain ranges for temperature, humidity, oxygen, and light. Our idea of indoor thermal comfort changes as we adapt to changing outdoor temperatures through each year. We also have individual differences and preferences that make designing a "perfect" space for all occupants improbable. The definitions and descriptions of human comfort are used as the baseline against which building performance is evaluated.

As an example, discussions on the acceptable comfort zone were instrumental in reducing energy use and the initial cost of DPR Construction's offices in Newport Beach. Their previous Net Zero Energy offices had experimented with the maximum interior temperature, finding that 83°F or more did not evoke complaints when large, overhead fans provided air movement. First-hand experiences with an expanded comfort zone, plus additional research, allowed the team to reduce the number of operable windows retrofitted into their Newport Beach offices for natural ventilation, saving capital costs and reducing the amount of time the mechanical system is used. See Case Studies 9.4 and 10.6.

As a negative example, a daycare project that achieved a high LEED rating used significantly more energy than projected. During the Value Engineering process, the team substituted airflow vents for natural ventilation, while also providing sapling shade trees instead of horizontal shades per the design. The substituted vents did not close completely, so the occupants adapted by bringing in space heaters during winter. In addition to using more heating energy than expected, there were several days each summer when the trees did not provide enough shade and the internal temperatures were too high for the children's health.

If comfort is the absence of discomfort, it is well beyond the scope of this book to address all possible sources. The focus for this chapter is on thermal comfort. Air quality is important to human health and affects energy use, but is not covered here. Visual comfort will be covered in Chapter 8 on daylighting.

Providing comfort in low-energy buildings is one of today's environmental design challenges. In the recent past, a narrow range of indoor temperatures have been assured by over-sizing building systems by a factor of 2 or even 3, which reduced their operating efficiency. Right-sizing these systems, which reduces capital cost and operating energy use, requires a more thorough investigation of expected building operations, better energy modeling, and an understanding of human comfort conditions.



3.1 *(top left)*

Human comfort is the measure of building performance.

Source: Original thermal images courtesy of Phil Emory of Neudorfer Engineers.

3.2 *(top right)*

Thermal images showing surface temperatures of four people. The two in the middle have higher metabolic rates than the two on the edges.

Source: Courtesy of Phil Emory of Neudorfer Engineers.

HUMAN THERMAL BALANCE

While most people's preferred environmental temperatures are in the 70s (°F), our healthy, internal "core" temperature is 98.6°F. For this reason, we are generally net exporters of heat to our environment. Thermal comfort is therefore based on people's ability to shed the right amount of heat.

We dissipate heat to our environments through: (1) inhaling cooler air and exhaling warm, moist air; (2) radiating heat from exposed skin to surrounding surfaces; (3) air movement wicking heat from clothing and exposed skin, as well as evaporating sweat to provide evaporative cooling; and (4) conduction/radiation through our clothing and feet to surrounding surfaces and air currents. When these methods become less effective due to environmental conditions, we can overheat. For example, high humidity reduces the effectiveness of sweating, while a high air temperature can reduce the effectiveness of 1, 2, and 4. All of this dissipated heat from people becomes part of the building cooling energy load as described in Chapter 10.

We gain heat by burning calories, being in contact with a hot breeze or object (electric blanket or hot coffee), or being in the radiant path of a heat source such as the sun, a fire, or a hot radiator.

WHAT AFFECTS THERMAL COMFORT?

Thermal comfort, or dissipating the right amount of heat to our environment, depends on a balance between four factors controllable by building systems: air temperature, mean radiant temperature, air speed, and humidity. Two additional factors are based on the occupants themselves: metabolic rate and clothing insulation. The adaptive comfort model adds other factors: local outdoor temperature history and some aspects of psychology.

Most people associate thermal comfort with air temperature. Home thermostats cycle on and off based solely on air temperature, and furnaces supply warm air to adjust the air temperature. Studies show that human thermal comfort is actually more dependent on mean radiant temperature (MRT), which is only indirectly affected by warm or cold air supply. MRT is the average temperature of the surfaces around us, modified by their surface emissivity and our geometric location within a space. Many low-energy buildings use radiant heating and/or cooling, since it is a more effective (and efficient) method of providing comfort.

All surfaces constantly exchange "long-wave" radiant energy, heating up cooler ones and cooling warmer ones. We constantly send and receive radiant energy as well, and the perceived thermal comfort of a space is largely based on the quantity of radiant energy we receive. An auditorium, a party, or packed conference room can overheat quickly, partly due to people exchanging radiant temperatures with 90–95°F skin instead of with 65°F walls.

Air speed helps dissipate heat by removing a layer of air that heats up around us, and providing airflow that increases evaporative cooling through sweat. Airspeed is often controlled through natural ventilation, a mechanical airflow using fans within ductwork, or overhead fans.

The last factor controlled by building systems, humidity, is often tempered by a mechanical system. A heating system lowers the relative humidity of cooler outdoor air. Warm, humid outdoor air is usually cooled to 55°F, which drains moisture (called condensate) out of the air. This air is then brought into a space, mixing with warmer indoor air, lowering the space's relative humidity. It is interesting to note that, though humidifiers are common in cold climates, the ASHRAE 55 comfort standard has upper limits for humidity, but no lower limits.

Clothing insulation and the metabolic rate of occupants also affect an individual's comfort level. A typical level of clothing (measured in clo) is assigned to occupants: a clo of 0 is nude, while a clo of 1 includes a typical business suit. Metabolic rate (1 met = 18.4 Btu/h/ft^2, where ft^2 refers to a person's total skin area) is based on the activity level of the occupants. In an office, people are assumed to be fairly sedentary (met = 1.0–1.2) with pants, a shirt, and sometimes a jacket (clo = 0.8–1). In a gym, people will be fairly active (met = 2–7 or more) and wearing shorts or sweats and short-sleeved shirts (clo = 0.3–0.6). In some typologies such as swimming pools, spas, and on-mountain ski retail, people can be assumed to wear significantly less or more clothing.

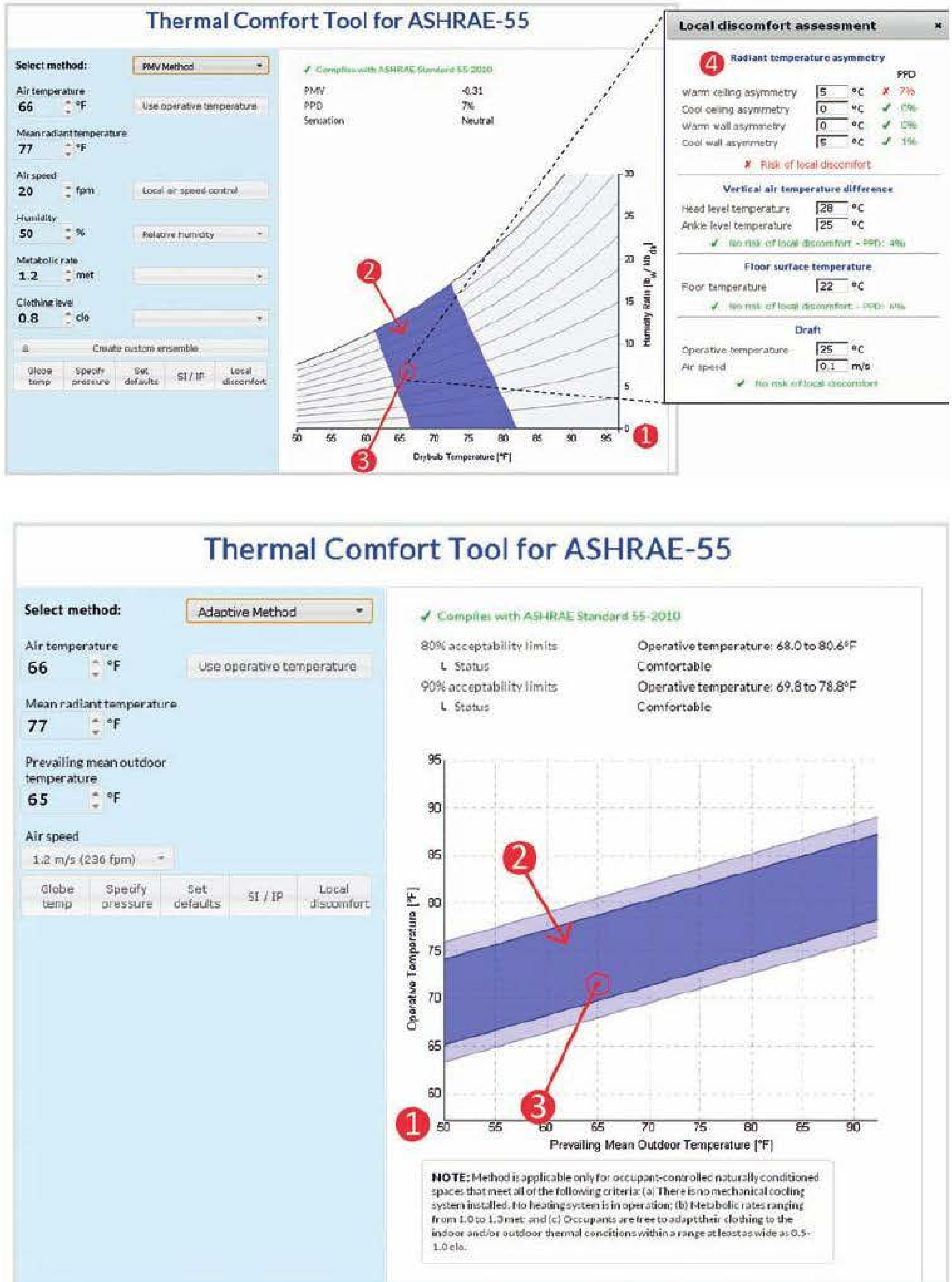
The science is much more detailed than presented here, including clothing permeability and layering, convection based on body position and exposure, and heat loss through each portion of the body. The *ASHRAE Handbook of Fundamentals* (ASHRAE, 2013) contains dozens of equations that help estimate heat transfer through clothing and metabolic rates. These equations, however, are often directly included in simulation software that reports thermal comfort, while simulation software that reports energy use is guided by one of the methods described below.

DEFINING THERMAL COMFORT RANGES

Human comfort is a soft science, relying on individuals self-reporting their satisfaction with their environmental conditions. Subjects are exposed to various combinations of air temperature, humidity, air speed, and MRT, and their responses reflect these environmental factors, plus psychology, age, culture, and thermal expectations. Due to individual differences, ASHRAE standards expect that 10–20% of the occupants of a given space may not be thermally comfortable, even in a well-designed building. Occupant controls increase thermal satisfaction, and will be discussed later in the chapter.

The two main definitions of thermal comfort, static and adaptive, are based on lengthy and detailed studies of individuals self-reporting comfort. Most of the studies ask occupants to rate their thermal sensations on a scale from –3 (cold) to +3 (hot), with 0 being thermally indifferent.

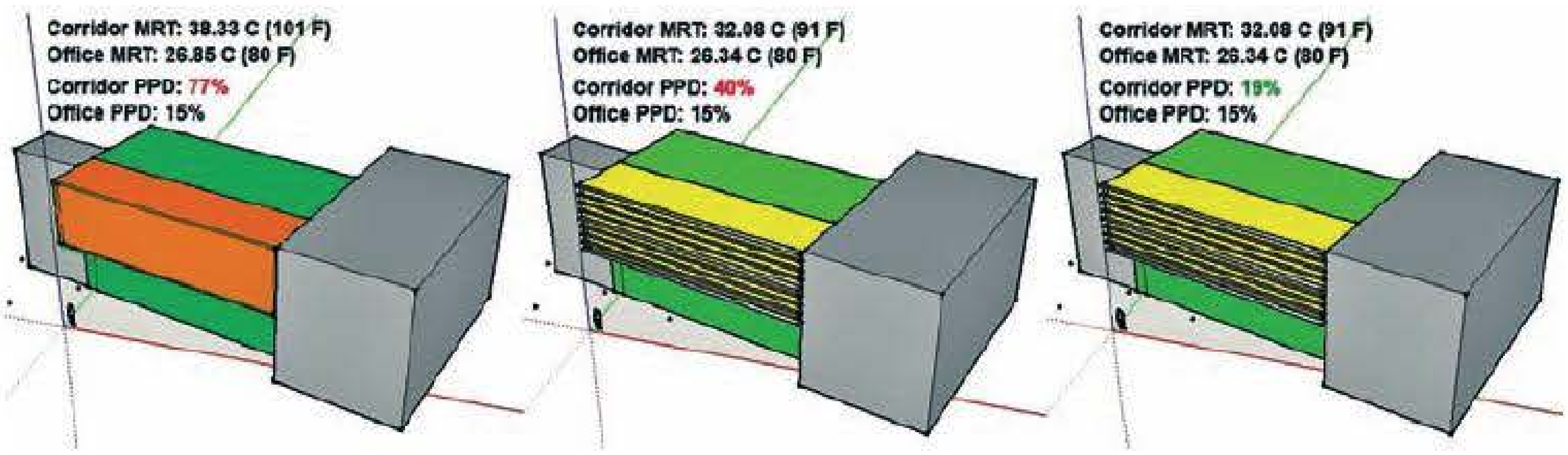
A space is considered to be adequately comfortable if the calculated mean thermal sensation response (the Predicted Mean Vote or PMV) is between –.5 and +.5. This range of PMV has been found in field studies to satisfy 80% of the average population. Due to individual preferences and differences and natural temperature fluctuations, achieving 100% PMV is not considered possible in a uniform environment.



3.3

A real-time, interactive comfort tool for indoor conditions based on ASHRAE-55–2010 from the University of California, Berkeley, can be used to understand the ranges for the Static (Predicted Mean Vote) and Adaptive comfort models. Note the different X and Y axis labels (1). The comfort zone (2) is plotted in purple. For the Static model, this area changes based on met and clo values, while the dot (3) shows whether a specific combination of environmental factors is predicted to result in thermal comfort. In the adaptive model, the comfort zone changes based only on air speed, while the dot (3) changes position, based on air temperature, air speed, and prevailing mean outdoor temperature, calculated based on the last week or more of outdoor temperatures. Asymmetrical discomfort (4) may occur due to a warm ceiling and cool floor.

Source: CBE Thermal Comfort Tool for ASHRAE-55, http://www.cbe.berkeley.edu/comforttool/.



3.4

Within a highly glazed corridor, the addition of blinds and an increase in the airflow can be seen to reduce discomfort. False colors are used to show the temperature of the corridor. The unshaded façade on the left can overheat beyond the capacity of a mechanical system to create comfort. Instead, the addition of horizontal shades were necessary to reduce discomfort, with increased airflow being necessary as well to reduce Percentage People Dissatisfied (PPD) below 20%, a common upper limit.

Source: Open Studio thermal comfort model, courtesy of Premnath Sundharam.

While studies control for the environmental factors covered in the previous section, there are many psychological and environmental factors that may influence self-reported thermal comfort that are not captured in the studies.

People's range of comfortable conditions changes throughout the year. An individual may be comfortable in shorts on a 60°F sunny day in the Spring, while on a 60°F sunny Fall day they may choose to wear a coat. The Static model in ASHRAE 55 defines Summer and Winter comfort ranges using temperature, humidity, air speed, and mean radiant temperature. Many studies have proved that mechanical systems operated within this range will consistently satisfy more than 80% of occupants, an industry benchmark for comfort.

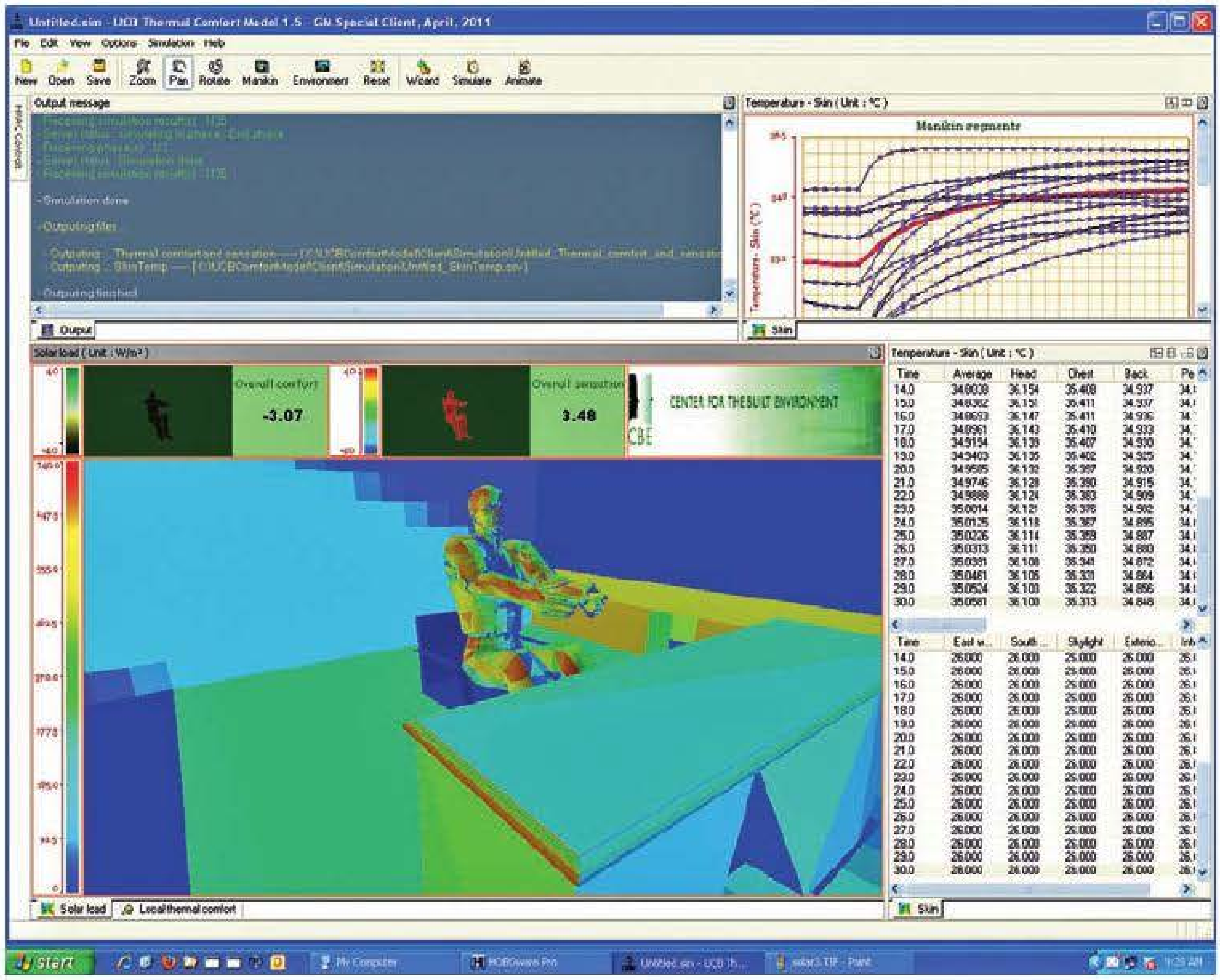
The Adaptive model asserts that people's idea of comfort changes daily and weekly, especially in relation to recent, local outdoor temperatures. This is known as acclimatization. The degree to which an environment meets expectations, or is adaptable by the user, also plays a role. Instead of passively accepting a narrow range of acceptable temperatures, this model assumes the occupants will add or remove clothing to maintain their comfort within a slightly wider range of temperatures. The Adaptive model is especially effective for predicting comfort within naturally ventilated spaces.

Interpretations of the ASHRAE RP-884 database of naturally ventilated buildings show that occupants in naturally ventilated buildings prefer a wider range of temperatures than predicted in the Static model (Brager and de Dear, 2001), related to outdoor temperatures among other factors. Occupants of mechanically conditioned buildings also were shown to prefer the narrower range of comfort conditions which they were used to, hinting at the roles played by psychology and acclimatization in thermal comfort.

The Adaptive model is becoming more widely accepted, but needs more rigorous field studies to assess impacts. ASHRAE's Standard 55 for human comfort added an adaptive option in 2010. This allows the comfort design parameters to include recent outdoor temperatures.

The criteria of thermal comfort used on a given project can have major implications. When a project team is confident that a space can be 3°F higher during the summer, they can reduce the mechanical equipment size and first cost. Expanded comfort criteria, especially along with good shading and lighting design, can allow more efficient systems to be used, such as radiant cooling or natural ventilation, see case study 7.1.

First-hand experience with comfort ranges can be essential in determining if a client is willing to accept a wider comfort range. In Oregon's BEST labs, a comfort chamber has been built where all four PMV factors can be tightly controlled to find comfortable ranges. Radiant wall panels can be quickly adjusted to a new temperature, airflow, air temperature and humidity can also be controlled. Skeptical individuals are allowed to hold meetings in the comfort chambers, periodically reporting their comfort level. When they are finished, the combinations they reported as comfortable often surprise them.



3.5

The Berkeley Comfort Model software simulation shows a person sitting near a window with sunlight coming in from the left. The software simulates solar transmission through the glass, as well as all long-wave radiation exchanges with windows and walls, local temperatures, humidities, and air movements surrounding the body, and the person's clothing and activity levels. These contribute to the skin temperatures of the body (shown in false colors) which in turn contribute to the person's thermal sensations and comfort. Due to the strength of the solar radiation, there is local discomfort on some body parts that override the comfort on other parts, producing an overall comfort of -3.07, which rates as uncomfortable on a scale from -4 (very uncomfortable) to +4 (very comfortable), with 0 as the minimum threshold for comfort. The software is used by auto-makers, engineers, and other industries to predict human comfort.

Source: Image courtesy of the Center for the Built Environment.

COOL HEAD, WARM FEET: ASYMMETRICAL DISCOMFORT

The previous section assumed that a space was at a uniform temperature. Mean radiant temperatures may vary significantly near exterior walls, especially near highly glazed façades, causing asymmetrical discomfort.

Instead of assuming the body loses heat consistently across the entire surface, people shed heat asymmetrically. Hands and feet normally vary within a 10°F range but our core temperature varies less than 1°F in a healthy person. Studies conducted by the Center for the Built Environment at UC Berkeley model temperatures over 16 parts of the body—arms, legs, head, and others, with each receiving unique temperature signals. Discomfort can be predicted if some parts are significantly warmer than others.

For example, if the left side of the body faces a cold window, enough radiant heat may be lost to the window that, even though the four comfort criteria described above are met, an individual reports being uncomfortable. Super-insulated buildings and those with thermal mass tend to have more consistent MRT and air temperatures, even near windows, and thus have reduced potential for asymmetrical discomfort.

OTHER INDOOR COMFORT FACTORS

Visual discomfort, or glare, can quickly turn a well-daylit space into one with blinds drawn and artificial lighting on. In addition to contrast glare, visual comfort is affected by the color temperature of the lighting, the specularity of surfaces, the balance of lighting levels within the field of vision, and other factors. Visual comfort is covered in more detail in Chapter 8 on daylighting.

Air quality also affects indoor comfort. Before buildings were well sealed, air flow through the envelope generally dissipated mold, spores, volatile organic compounds (VOCs), dust, and other airborne particles. In tighter buildings with more chemical-laden indoor furnishings, poor air quality results from not cycling enough fresh air through a space, which can increase sick days, asthma, and many other maladies. A study of asthmatic children found that transitioning their families to homes with good air quality reduced emergency room trips by 66% (*A New Prescription*).

CONTROLS: AUTOMATED, MANUAL, AND INTERACTIVE

Building control systems are becoming more sophisticated, an play an integrated role in nearly every aspect of building performance, though not without their problems. Excluding installation and maintenance, problems are often a result of the design team not considering the character and extent to which building occupants will be engaged in the energy performance of their building.

Automatic controls are tied into a building management system (BMS) to operate heating and cooling systems, blinds and shades, electric light dimming, operable windows and trickle vents, fans, and others. A BMS can also monitor roof sensors for wind, solar energy, and temperature, as well as read occupancy sensors and photosensors to aid in predicting heating and cooling loads and controlling the systems.

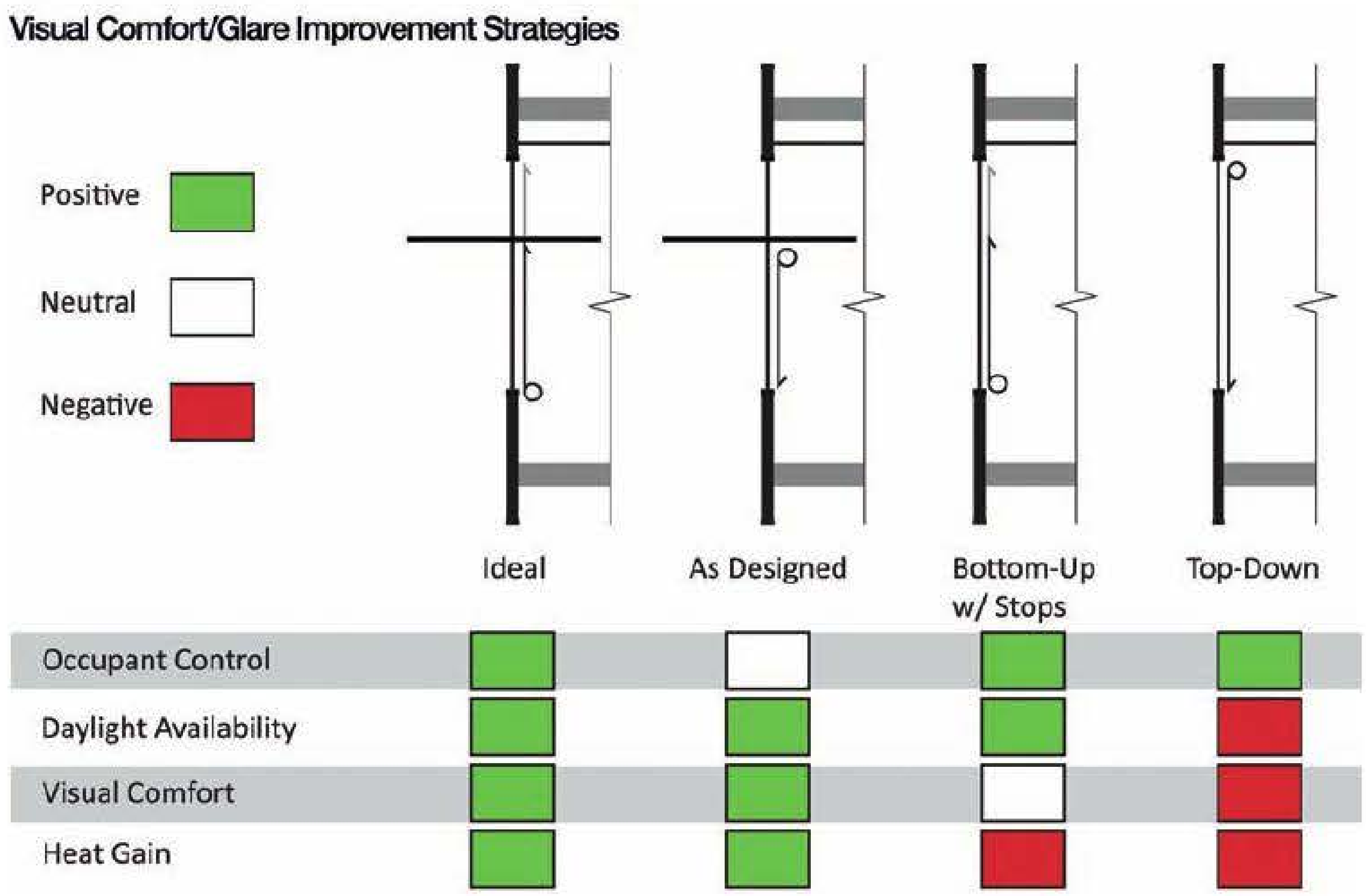
Automatic controls require the set-up and maintenance by a sophisticated user. In most buildings under 50,000ft^2 there is no dedicated facilities manager, so the programming and repair of automated components are often neglected. For larger projects, mechanical engineers generate sequences of operations for automatic controls. The contractor needs to determine how to wire it, provide actuators for moving parts (such as blinds, operable shading, automatic windows), and locate photosensors and CO_2 sensors, while the facilities manager needs to incorporate weather forecasts and on-site weather stations, and tie all of them into the BMS software. When these are not complete to exactly match the design intent and assumptions, the theoretical energy savings from the energy model do not materialize.

The author helped design a small building where expensive, sophisticated, automatic controls (with large theoretical energy savings) resulted in lighting that automatically turned off every day at 5 p.m. The staff member who was briefly trained to program the system was not able to recall the training,

3.6

A study prepared for Iowa State University by ZGF Architects LLP rates four window options for user controllability, daylight availability, visual comfort, and heat gain. While simulations predict lighting energy savings due to the use of daylight, these savings are only realized when the system successfully blocks glare or allows users to block glare without blocking daylight.

Source: Courtesy of ZGF Architects LLP.



meaning that someone had to be stationed near the lights during meetings that ran past 5 p.m. to immediately turn the lights back on.

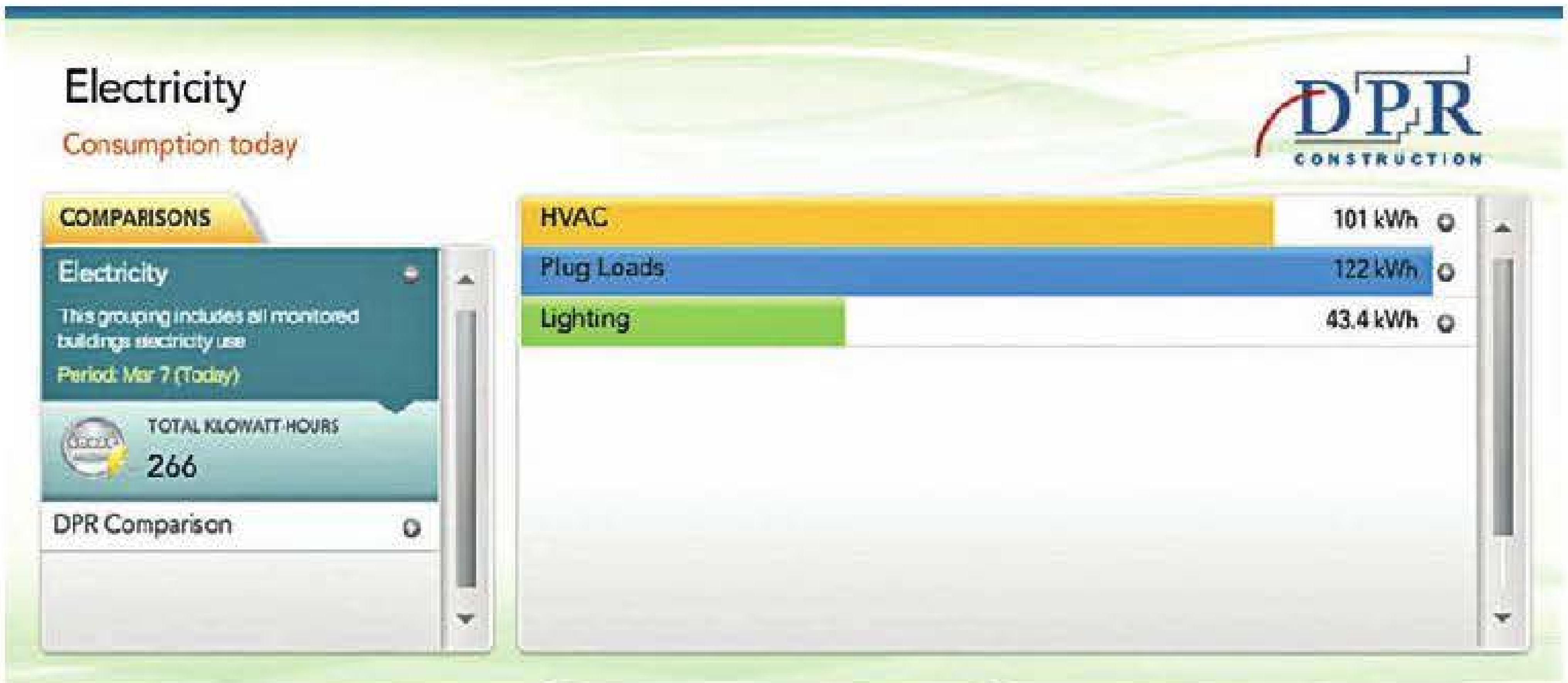
Automatic controls can result in large theoretical energy savings, often assuming that individuals are passive recipients of comfort. However, occupants generally want some control over the spaces where they spend long periods of time, such as offices, homes, hotel rooms, and hospital patient rooms. Often occupants will try to override automatic blinds to maximize their view or reduce the glare, block air vents to reduce unwanted cool air or high air speeds, or purchase space heaters in an attempt to create comfort conditions.

Studies looking at the adaptive thermal comfort model have found that people self-report higher levels of comfort when they have some control over their thermal environment. Local temperature or air flow controls, operable windows, operable blinds, and other mechanisms cede some control to occupants, with higher theoretical comfort levels.

Manual controls are not foolproof, either. They need to be located in logical places, often adjacent to the system they control for ease of use or else may be ignored. On a sunny afternoon when the majority of the occupants are away, operable windows may not be opened if they are manual, resulting in increased HVAC cooling instead of natural ventilation. Manual blinds closed to block a few minutes of glare often end up blocking light and potentially desirable solar heat all day. Automated systems would retract neglected blinds when the right outdoor conditions are present.

When determining whether manual and automatic controls are to be used, the architect is encouraged to understand and graphically present how occupants are likely to use each space—daily and seasonally—to mitigate glare, control thermal comfort, and enjoy views.

As part of this effort, the information and controls available to occupants can be important. Similar to cars that display a driver's current fuel efficiency, a dashboard that shows building occupants their current energy use can create a culture that is more aware and proactive about turning off lights, operating blinds, and opening windows for natural ventilation. Locating a dashboard on each person's computer or tablet can alert people, similar to the alert when an email arrives, that interaction with their environment may be required.



3.7 and 3.8

Great design strategies are more effective when energy use becomes part of everyday consciousness, conversation, and action by those who occupy the building. An online, real-time energy use tracker is a way of engaging occupants in building operation using software deployed to workstations, tablets, and phones. The dashboard for DPR Construction's Newport Beach office tracks building energy use against goals, past performance, and other metrics.

Source: Courtesy of Lucid and DPR Construction.

Chapter 10 discusses how user and automatic controls and user assumptions can become part of energy models. A simple shoebox model can help estimate the effects of controls on energy use. For a retail design in Phoenix, four different interior blind control assumptions led to a 5% difference in PMV and an 11% difference in energy use.

CONCLUSION

Many energy use decisions are made with reference to providing human comfort. As the case studies throughout this book show, low-energy design also requires a consideration of how occupants can control their environment, and supplying them with the right information and controls helps them ensure their own comfort with little energy use. An architect cannot expect building users will understand how all the building systems interact in low-energy buildings, so a balance must be struck between using automated and manual controls with simple user engagement.

4
Climate Analysis

Climate is what we expect, weather is what we get.

—Mark Twain

Our climates used to define us—available food, typical clothing, seasonal customs, and vernacular architecture all responded directly to challenges and opportunities posed by each climate. A photograph of a modern building gives nearly no indication of its climate—shading, orientation, massing, or otherwise. Low-energy buildings often opt for regionally appropriate characteristics, which may be significantly different from historical vernacular. They are often asymmetrical due to weather conditions and sun angles.

We are beyond the brief period when coal and oil energy shielded us, seemingly without consequence, from designing for climate. Most citizens accept that fossil fuel energy is the major contributor to global climate change. We also know that shielding ourselves completely from nature is not even desirable: biophilic human interactions with daylight, views, vegetation, and seasonal changes have positive health and productivity benefits.

Just as most building energy questions are rooted in creating human comfort, the creation of comfort is based on how buildings interact with ever-changing outdoor conditions. Each case study in this book illustrates how architects have used climate data within simulations to determine or validate appropriate climate responses.

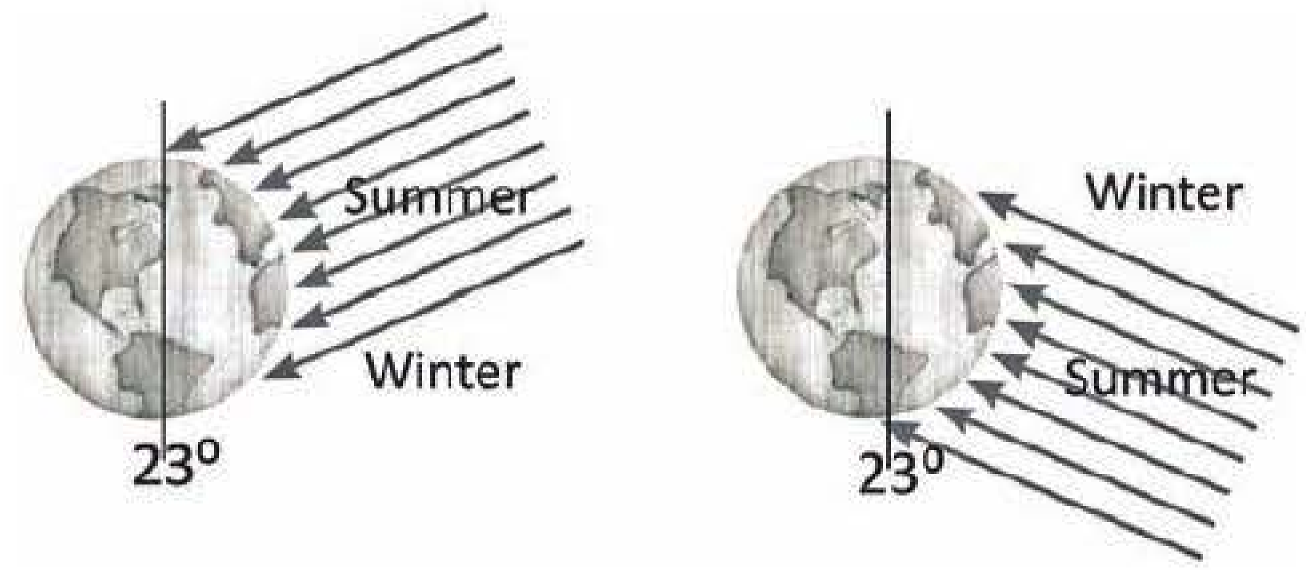
Many sustainable design resources recommend strategies based on climate classification, which serves as a starting point for design. Since climate classifications are necessarily general, each potential strategy needs to be validated within a micro-climate with experience or simulation. To evaluate climate-responsive design with software, practitioners need to understand how temperature, humidity, wind, solar irradiation, and other factors can influence building design. They need to understand how weather is recorded and used in building simulations, and how location-specific factors make a micro-climate unique from the nearest weather data.

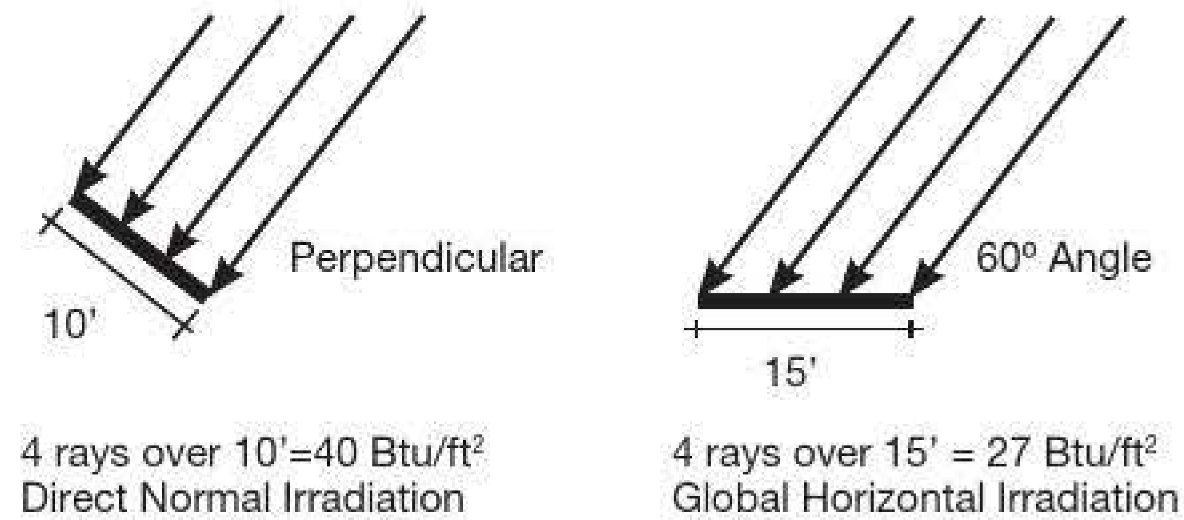
THE INTERACTIONS THAT CREATE WEATHER

Our sun and its constantly changing relationship to the Earth generate nearly all climatic conditions on Earth. What we refer to as weather are the effects of global patterns on the thin layer we inhabit near the Earth's surface.

Our sun emits energy (light and heat) as short-wave radiation. Around 435 Btu/h/ft^2 is received by the upper atmosphere. Sunlight is scattered by molecules and dust particles and absorbed by ozone, mixed gases and water vapor, including clouds and smog; a maximum of around 320 Btu/h/ft^2 actually reaches the Earth's surface. Sunshine scattered by the atmosphere becomes a source of ambient light and heat.

The angle between the sun's rays and the ground determines the density of energy striking the Earth's surface. Sunshine perpendicular to its surface delivers much more energy per unit area than at





4.1 and 4.2

The angle at which the sun's rays strike the Earth determines the overall heat absorbed. The higher and lower sun angles are the major drivers in creating seasons.

Source: Amal Kissoondyal.

any other angle. Low winter sun angles, combined with fewer total hours of solar irradiation, result in significantly less energy delivered during winter. This principle, plus some atmospheric effects, results in seasons.

CLIMATE DATA

Climate data is much more local, accurate, and available than it was a few decades ago. Charts of solar angles, sun path diagrams, and generalized climate types have given way to city-specific climate data collected at airports that can be graphed or used as an input into design simulations.

There are many ways to visualize the data, and each sustainable strategy requires the study of a unique combination of climate data inputs. Some methods of looking at the data are included in this chapter, but the reader is encouraged to learn to convey climate information to produce outputs unique to the building design and strategies being considered.

There are generally two ways that climate data is packaged for use in building simulations: (1) annual weather files, which contain data for each of the 8760 hours in a typical year; and (2) peak condition files. Annual weather files are used to produce annual energy use simulations, such as Energy Use Intensity (EUI) studies. Peak condition files are used to help simulate how comfort may be created under a climate's most extreme conditions. Simulations using peak data are used to select and size mechanical systems, a major consideration in a project's first and life-cycle costs.

A weather file includes climate data plus information about the weather station such as: latitude and longitude, time zone and daylight savings observance, altitude above sea level, and other site information. The solar path is not recorded in weather files since software can instantly calculate it based on latitude and longitude. In addition, it usually records the following metrics at least once each hour:

Air temperature (dry bulb)	Wind direction and speed
Dew point temperature	Relative humidity
Wet bulb temperature	Absolute humidity
Global horizontal radiation	Cloud cover
Diffuse horizontal radiation	Rainfall
Direct beam radiation	Illumination levels

ANNUAL DATA SETS

Annual data sets often include hourly measurements of the above variables, so each day has 24 entries for each variable and each year has 8760 entries. Modern annual weather data used for annual design simulation began with Typical Meteorological Year (TMY) data and was refined for TMY2 (1961–1990) and TMY3 (1991–2005) data sets. In the USA, the Sandia method (named for the Sandia National Labs) uses algorithms to select the most typical hourly weather readings in January from the measured data

4.3

While weather data is typically collected at airports, wind data for natural ventilation simulations is best informed by local data. A weather station was located across the street from the Net Zero Energy Bullitt Center to provide site-specific weather data that can be used to calibrate city-specific data.

set based on five weighted factors. Other months are similarly selected to produce a synthetic "typical" year, and then the months are smoothed so that they join together to form a full year. Whole building energy simulations, all of the graphic climate information in this book and nearly all of the case studies use freely available TMY2 or TMY3 files. More information can be found in the *Users Manual for TMY3 Data Sets* (Wilcox and Marion, 2008).

This annual weather data has been translated into the popular EnergyPlus Weather (.epw) file format, available on the US Energy Efficiency and Renewable Energy (EERE) website. Thousands of TMY2 and TMY3 files are available for free download, covering most of the world's large cities (see http://www.nrel.gov/docs/fy08osti/43156.pdf, for TMY3 files). More information about the files and weather collection sources are available on that website. Private companies, such as Weather Analytics, also sell hourly weather files in standard formats if one is not freely available.

Actual Meteorological Year (AMY) files contain one specific year of data. This can be useful to compare the predicted performance of a building to actual performance, correcting for actual weather conditions in a given year instead of averaged TMY files.

For projects with enough time, a weather station can be located on site to get hyper-local data for one or more years to collect raw data. This can be especially important for wind data in urban or hilly regions.

There are now hundreds of thousands of weather stations around the world collecting raw, micro-climate data, though in many cases the data has not been verified or interpreted. Weather stations can cost between hundreds and tens of thousands of US dollars, plus the labor of extracting and interpreting the raw data. Installing the station requires guidance, as a nearby glass façade, for example, can affect the measured solar radiation (by reflection) and wind velocity (by blocking or re-directing). Parsing the raw data to generate a useful weather file can also be a challenge. Airport stations usually have no obstructions nearby to skew the data.

4.4

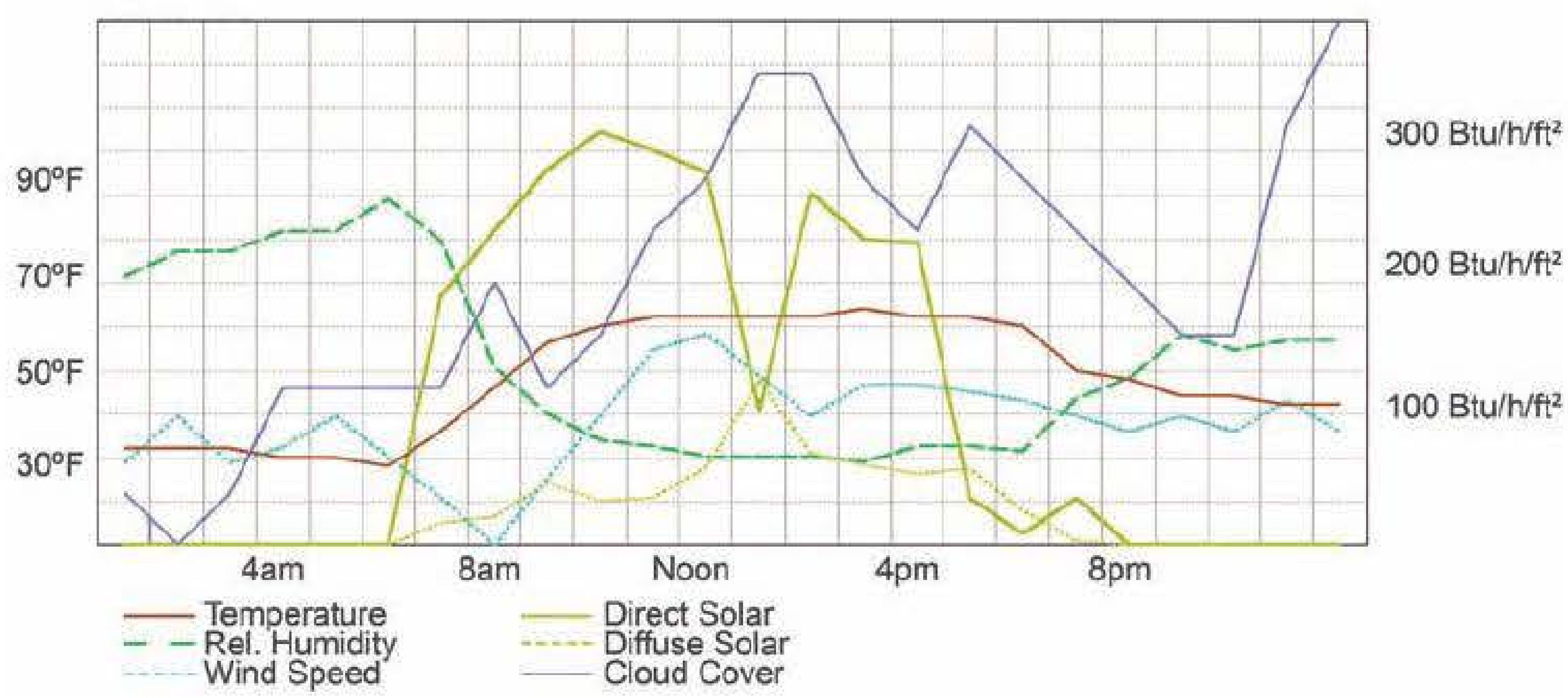
A weather data layer for Google Earth on the US EERE weather file site shows EnergyPlus weather file locations. This allows a designer to compare nearby weather files for the best site match, accounting for any change in elevation, proximity to mountains or water bodies, as shown in Case Study 5.3. Google Earth images use data from SIO, NOAA, the U.S. Navy, NGA, GEBCO, Cnes SpotImage, Terrametrics, and IBCAO.

On-site weather stations or other local, raw data generally spans only a few years and does not represent the long-term weather patterns, so it will not give reliable results for annual energy use simulations. However, this data can be useful. As an example, for a naturally ventilated building in Bothell, WA, LMN Architects wanted to know what the climatic differences were between the site and the nearest TMY data (Boeing Field) that would be used to run the annual energy model. If Bothell was typically several degrees warmer than Boeing Field on the hottest days, natural ventilation would be very difficult. Discontinuous weather data recorded on-site in Bothell was compared to AMY data from Boeing Field recorded over the same period. For the hottest group of days, temperatures were found to be nearly equal, with the main difference being higher diurnal swing and higher nighttime relative humidity in Bothell. Both of these were attributed to the adjacency of wetlands to the Bothell weather station.

To anticipate a changing climate, some organizations (such as the University of Exeter) have produced peer-reviewed "future" climate files, including multiple climate change scenarios.

As a caveat, annual weather files include average conditions while weather differs every year. For example, El Niño and La Niña years experience warmer and cooler ocean temperatures (respectively) in the Pacific, with global consequences. El Niño is associated with wetter winters and floods, as well as changes in wind patterns, lasting 12–18 months and occurring every 3–4 years. Ski resort operators, farmers, and power companies understand these yearly weather deviations, since they affect their businesses.

A robust design will reduce energy in nearly all years, even those that are fairly different from the design weather file. Buildings designed to be Net Zero Energy using average weather files will be Net Zero on average, but not necessarily in every year. As an example, the first year of operation of the Bertschi School in Seattle (Living Building Challenge Certified, including Net Zero Energy) included a winter that was colder and darker than the TMY data used in the energy model. This led to an increased



4.5

A 24-hour period set of data from a weather file shows the interaction of the dry bulb temperature, the relative humidity, the direct solar, diffuse solar, wind speed and cloud cover. Note the inverse relationship of temperature and humidity; direct and diffuse solar irradiation; and the inconsistent relationship between cloud cover and direct solar.

Source: Autodesk Ecotect Suite output of EnergyPlus weather data. Courtesy of Callison.

heating requirement and decreased photovoltaic production. The second year of operation, a more normal year, allowed the building to achieve Net Zero Energy.

PEAK DATA SETS

Mechanical systems are sized to create comfortable conditions under peak loads, which convey the most extreme conditions regularly seen within a climate. Peak loads have traditionally been calculated using design day (.ddy) sets of outdoor conditions found in the climatic design data in the *ASHRAE Handbook* (ASHRAE, 2013). This data on the hottest and coldest conditions has been copied into .ddy files that are downloaded from the EERE website alongside annual .epw files.

A system designed to meet the "99.6% design day peak heating conditions," for example, will maintain comfort conditions for 99.6% of the hours each year in terms of heating load. The remaining 0.4% (35 hours each year) can be met by oversizing the system or due to occupants' expanded comfort range based on recent outdoor temperatures, though this is not specifically addressed in the static model. A system designed to meet the same standard for cooling uses "0.4% design day cooling conditions."

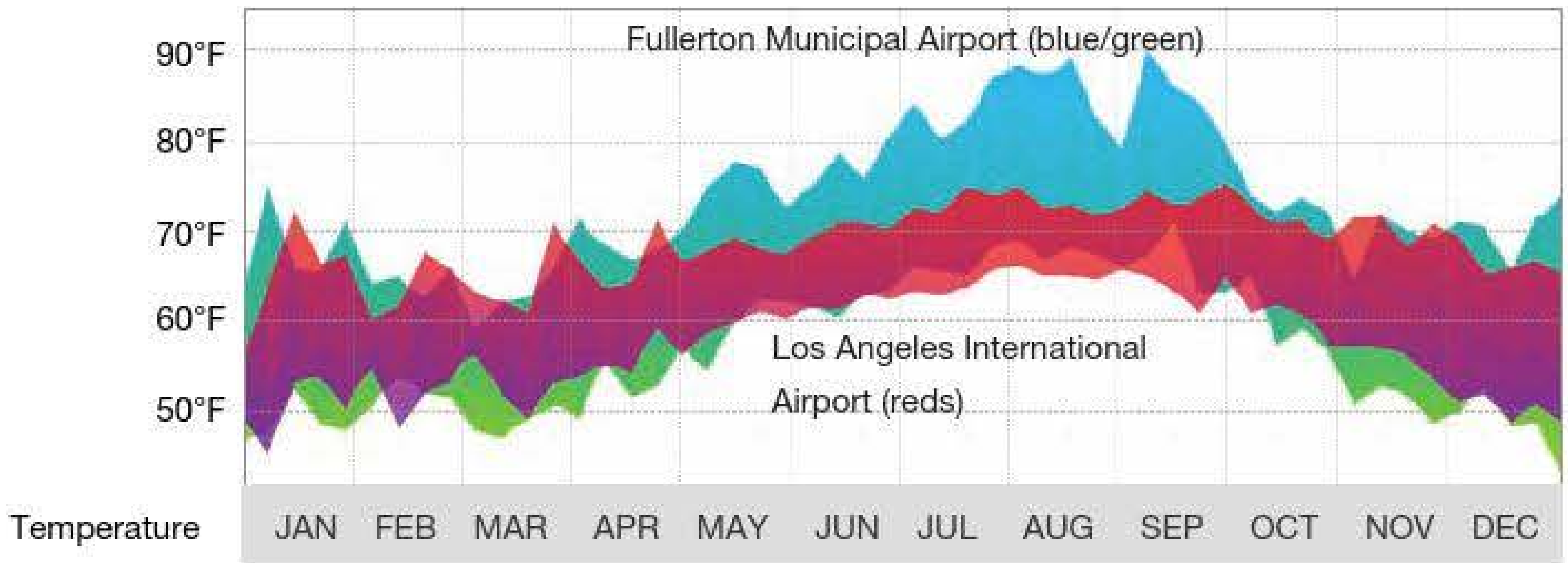
Each peak heating and cooling condition is assigned a specific day so the sun's path can be calculated. Files also include a sky clearness from 0 to 1.1, with 0 being overcast and 1.0 being sunny. Design day files contain multiple types of peak heating and cooling scenarios, which can be opened in a text file for inspection.

Since only one type of peak data set is constructed for each climate, this information can be too generic for low-energy buildings. For example, the Edith Green–Wendell Wyatt project team used March 15th as the peak cooling day for analysis of the south façade, due to the low sun angle. Each façade was assigned a different peak cooling day, see Case Study 7.1.

TEMPERATURE

Air temperature is the most commonly understood factor in thermal comfort, central to any weather report. Technically it is referred to as *dry-bulb temperature*, and is measured when a thermometer is shielded from solar radiation and dampness. A *wet-bulb temperature* is recorded by a sling psychrometer, essentially a thermometer with a damp cloth over it that is moved through the air. As the dampness evaporates, it reduces the temperature reading. At the temperature where relative humidity reaches 100%, also called the dew point, wet-bulb and dry-bulb measurements are equal.

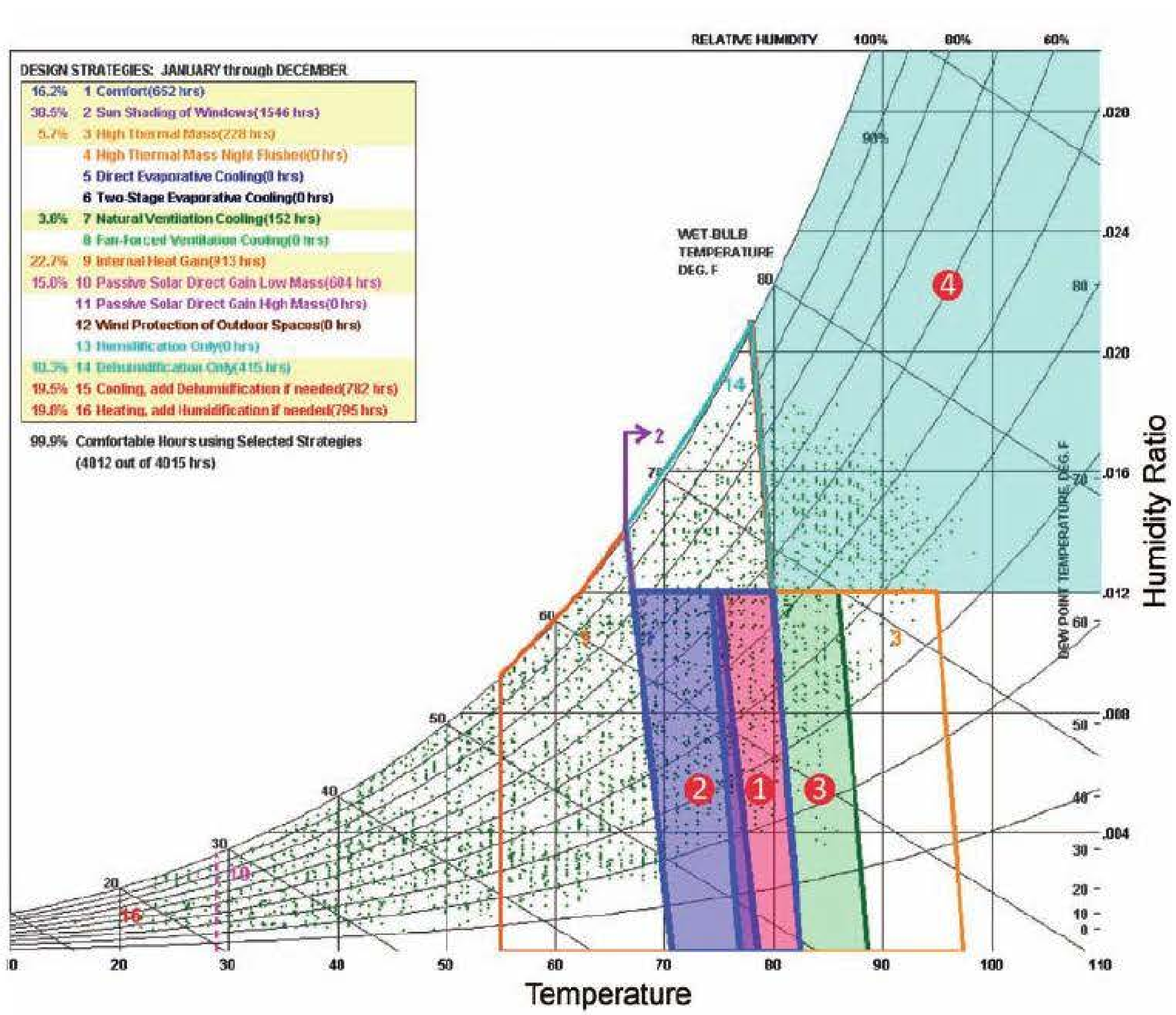
While not part of weather files, Heating Degree Days (HDD) are a general measure of the quantity of heating required for a climate. Each degree that the average daily temperature is below the threshold



4.6

Comparison of annual average temperature profiles from Los Angeles International Airport (LAX) weather station, 2 miles from the Pacific Ocean, and Fullerton Municipal Airport, 11 miles inland. Fullerton gets much hotter in summer than LAX and has a wider diurnal swing. This is due to being farther from the coast, resulting in lower humidity, proximity to the LA's urban heat island effect, and other factors.

Source: Courtesy of Callison.



4.7

Climate Consultant output of a psychrometric chart with interactive sustainable strategies. The chart shows temperatures along the horizontal axis and humidity along the vertical axis. Each hour of the year within the occupied time (8 a.m.–6 p.m. for this office project) is plotted for temperature and humidity with a green dot. Each hour where the combination of temperature and humidity naturally provide comfort are enclosed by the Summer (1) and Winter (2) comfort zones. Strategies that can provide comfort are listed in the upper left; each one encloses additional area of the chart, showing that it will provide comfort under those conditions. For example, Natural Ventilation (3) encloses those areas that are up to 6°F warmer than the comfort zone, but not more humid. According to the tool, Natural ventilation will work 3.8% of the occupied hours. Hours that are both too hot and too humid require mechanical cooling (4); based on the strategies selected, 19.5% of the annual hours require mechanical cooling.

Source: Courtesy of UCLA Energy Design Tools Group, http://www.energy-design-tools.aud.ucla.edu/.

(HDD65 uses 65°F) counts towards the total. For example, if the average temperature on November 17th is 30°F 35, (65° minus 30°) is added to the monthly or yearly HDD65 total. Days with average temperature above the threshold are not counted. Cooling Degree Days are calculated in relation to a baseline the same way. New York City has a 30-year average of 4780 HDD65 and 1140 CDD65, while Atlanta's average is 3100 HDD65 and 2060 CDD65. Standard measurements are often based on HDD65 or HDD60, but modern buildings with insulation do not require heating until outdoor temperatures reach 55°F or less. See Case Study 10.5.

Some ways that temperature is used in building design and simulation are:

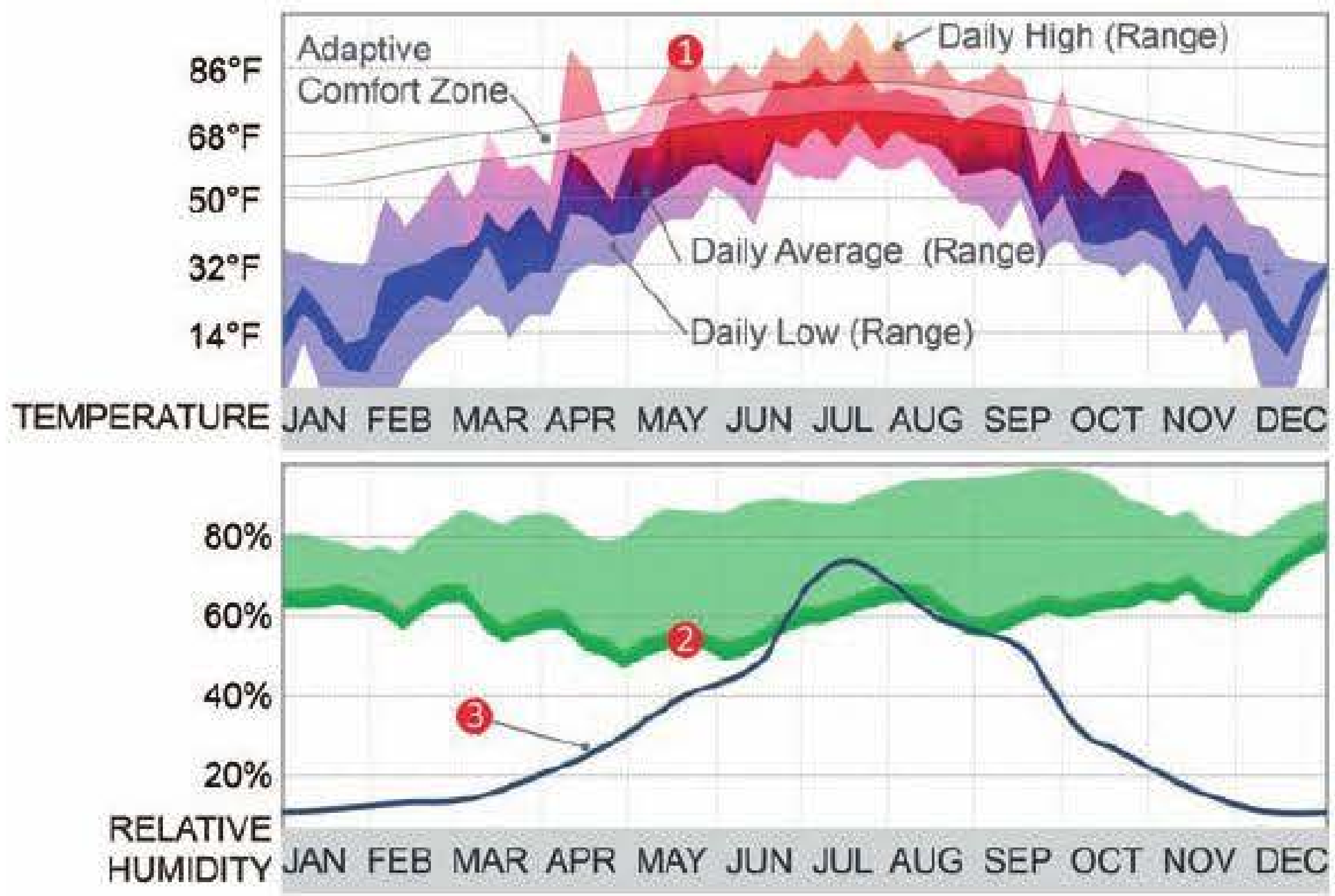
- Conduction loss or gain through the building envelope is based on the difference between the indoor and the outdoor temperatures, multiplied by the envelope's conductance, called the U-value. This is covered in Chapters 6 and 10.
- Prescriptive thermal insulation requirements are generally based on the number of heating degree days and cooling degree days.
- In cold climates, thermal bridges (such as a cantilevered concrete deck or a steel beam) can bring the outside temperatures in, increasing energy use and potentially condensing water from warmer interior air.
- People require fresh air to be brought into buildings to replenish oxygen levels and remove odors and pollutants; this air needs to be heated or cooled most of the time, requiring significant energy use in extreme climates.
- The Adaptive comfort model uses recent outside temperature history to anticipate the range of temperatures that people find comfortable indoors.
- Photovoltaics are less productive with high temperatures.

Micro-climate factors include:

- Topography, vegetation, colors and textures absorb and reflect the sun's heat in different ways.
- The urban heat island effect increases local temperatures, due to pavements storing solar energy, dark roofs absorbing heat during the day (reaching up to 160°F or more), and vehicle combustion and smog. According to modeling done in 1997 (*EPA Urban Heat Island*), Salt Lake City's urban heat island added around 7.2°F to night-time and 3.6°F to afternoon temperatures. The local peak power demand was increased by 85 mega-watts, with additional cooling costs due to the heat island effect around $3.6 million annually.
- Temperatures decrease 3–4°F for every 1000′ of elevation gain.

HUMIDITY

High humidity in warm seasons is associated with increased discomfort, since it slows the body's ability to cool down through the evaporation of sweat.



4.8

Profile view of daily high temperatures (1) are simultaneous with low relative humidities (2), meaning that the bottom half of the humidity profile shows the expected peak daytime humidity. This information is useful for calculating thermal comfort with natural ventilation strategies. A line (3) shows the indoor relative humidity when outdoor air is heated to 70°. During most winter months the indoor relative humidity would be less than 20%.

Source: Modified Ecotect output of TMY3 weather file from Minneapolis-St. Paul International Airport. Courtesy of Callison.

Relative humidity (RH) is the most commonly used measurement of airborne water vapor, describing the percentage of water in the air to the maximum amount that the air can hold. Since warmer air can hold more water, a day's highest temperature usually corresponds with the lowest relative humidity. For example, an RH of 100% at 60°F in the morning warms to 80°F by noon, resulting in an RH of 50% even though the mass of water vapor (absolute humidity) per volume of air has not changed significantly. When 95% RH air at 80°F is cooled down to 65°F, it will shed water. Mechanical systems drain this water, called condensate, which can be measured in gallons per day even for small cooling systems in humid regions.

During cold seasons, outdoor air that is heated up to indoor temperatures often has a very low RH. For example, when 20°F, 90% RH outdoor air is heated up to 70°F, the RH drops to 13%. At low relative humidity, people's eyes and lips feel dry and static electricity is increased. For this reason, people in cold climates often use humidifiers.

Some ways that humidity is used in building design and simulation are:

- High humidity provides outdoor thermal storage due to water's specific density, limiting the temperature swing from day to night.
- The ASHRAE 55 Predicted Mean Vote (PMV) comfort standard specifies a maximum range of indoor humidity levels, but no minimum.
- People, showers, cooking, improperly covered dirt crawlspaces, and other factors add humidity to indoor environments.
- Evaporative coolers (swamp coolers) add humidity to outdoor air in arid climates to reduce the temperature, increasing comfort.
- The dew point is important in hygrothermic calculations, as it determines where water will condense within a wall or roof assembly.

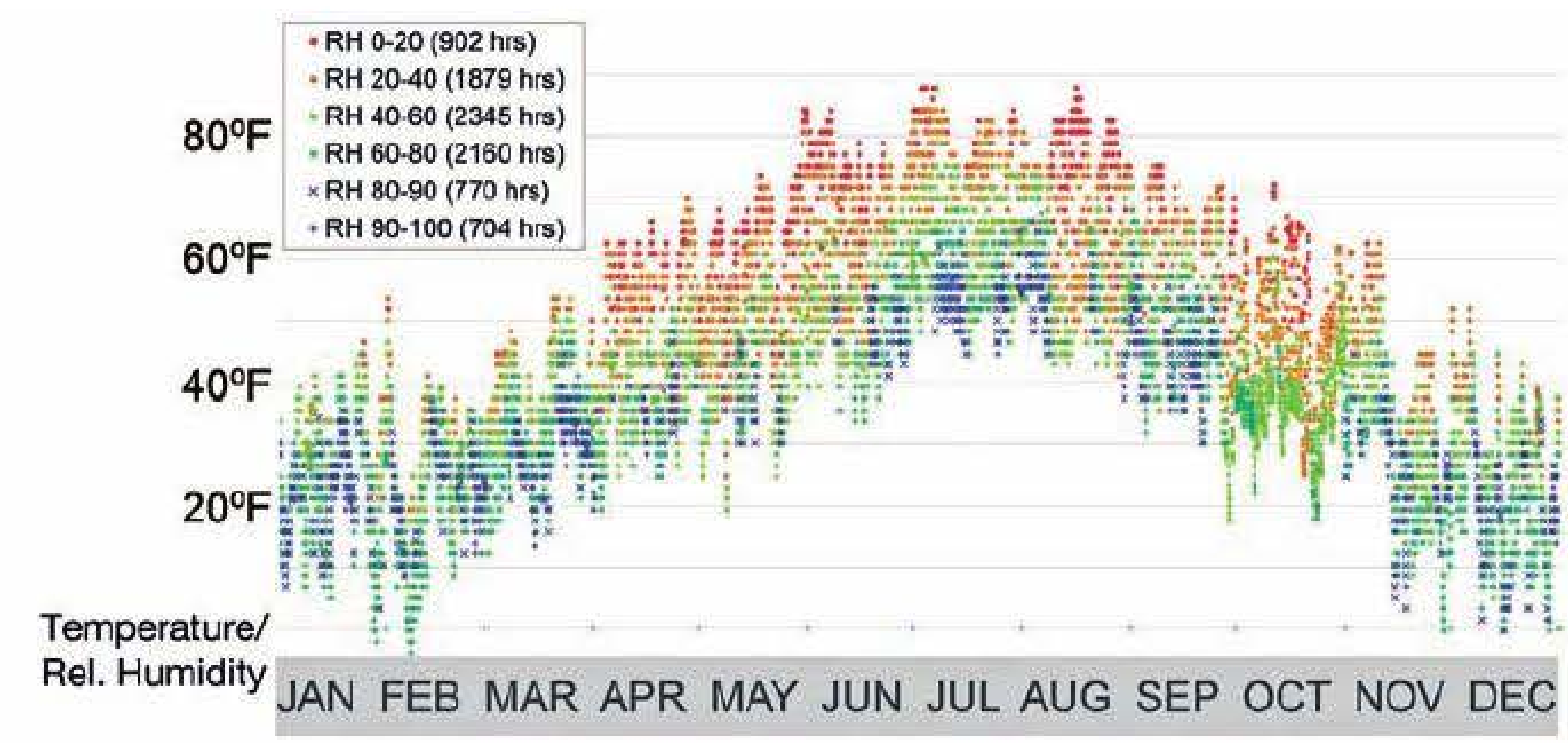
Micro-climate factors include:

- Vegetation increases local humidity through evapotranspiration.
- Water bodies tend to moderate the nearby climate with humidity, and daytime breezes tend to head inland from the water body.

4.9

Temperature and relative humidity can be combined to show the relative humidity at each hour of the year, providing a quick look at peak summer natural ventilation potential. Peak temperatures in Vail, Colorado, reach above 80°F with relative humidity between 0–40%.

Source: Excel output of TMY3 data from Aspen-Pitkin Country Airport. Courtesy of ZGF Architects.



SOLAR RADIATION AND CLOUD COVER

Our sun has been a source of constant fascination throughout history as it gives us heat, light, provides energy for our food, and its absence, until recently, ended the workday. While it follows a daily and annual path, the sun's constantly changing position relative to a building and the unpredictable distribution of cloud cover relative to the sun's position make design for solar and daylighting a challenge. Simulations can use an annual weather file that contains one example of how they may interact, a peak file that contains the most extreme conditions, or a general probability of how they may interact at a given time.

The sun's energy on a surface—one square foot of window, for example—is called insolation. A south-facing window at 10 a.m. may receive insolation of 250 Btu/h per ft^2 of window area. Over the course of 10 hours, the window may receive 2000 Btu per ft^2. This quantity can be translated into a heat source or a cooling load, once this energy has been transferred into a building. Available solar energy depends on cloud cover and the angle at which it reaches the Earth, and is easily mapped by design simulation software.

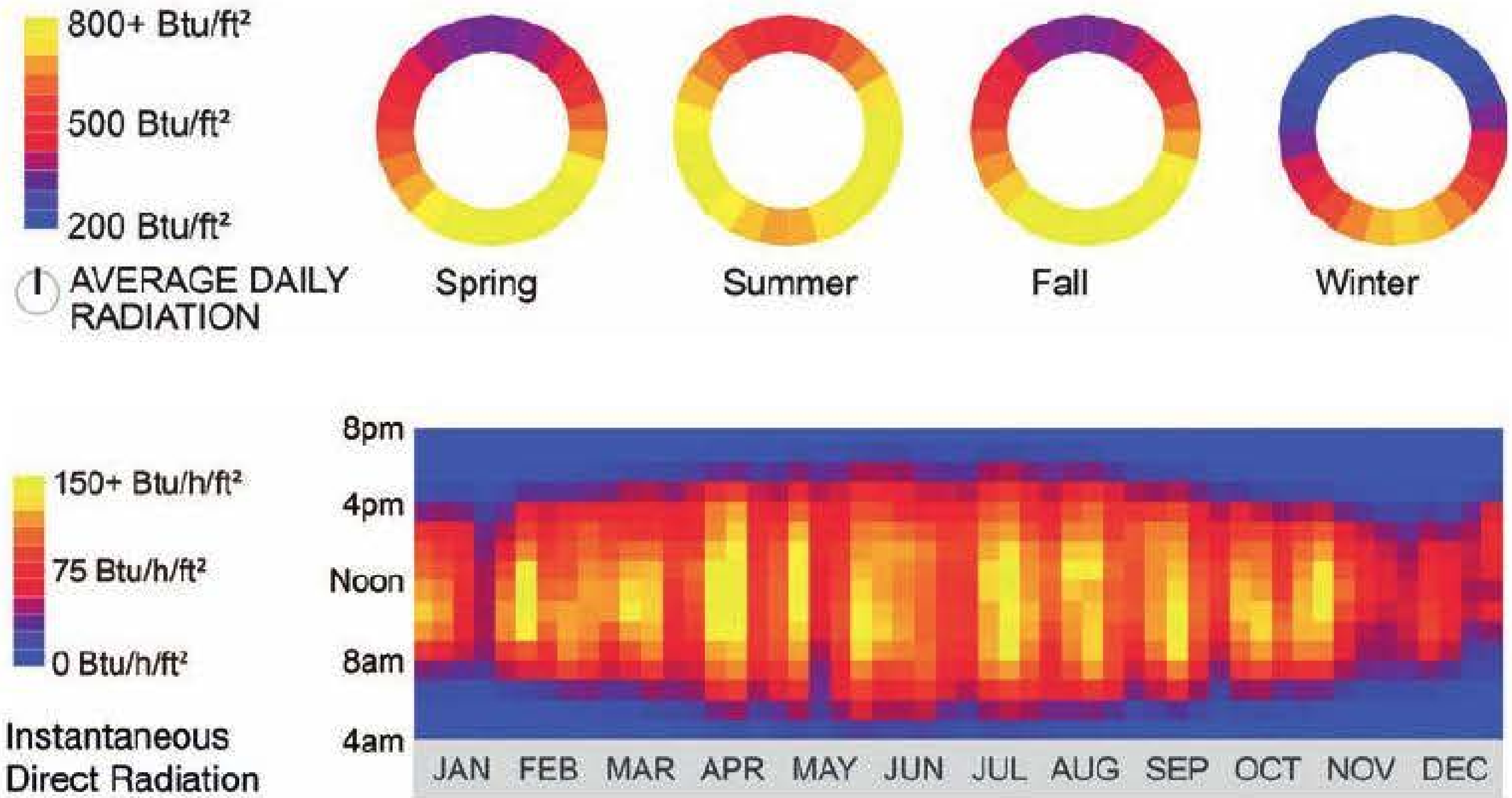
A weather file contains logs of direct irradiation, measured perpendicular to the sun's rays; global horizontal irradiation, which is measured on a flat horizontal surface; and global diffuse radiation, which includes all reflected radiation that does not come directly from the sun. Diffuse radiation is measured by locating a small disc between the instrument and the sun, thus removing the direct radiation component.

Cloud cover blankets the Earth, keeping heat from escaping. Cloudless nights tend to create colder mornings, due to radiative cooling. Clouds not only trap airborne heat beneath them, but also reflect radiant heat downward that would otherwise be lost into space.

Cloud cover is measured as an average percentage of sky coverage. The distribution of clouds constantly changes, and whether the sun reaches a building is entirely dependent on a specific vantage point at a specific time. Software often calculates the probability of the sun being blocked by clouds at a given moment.

Some ways that solar irradiation and cloud cover are used in building design and simulation are:

- Windows allow direct heat gain, which must be controlled as a heat source. Peak solar loads often drive mechanical system selection, sizing and cost.
- Irradiation falling on opaque surfaces increases conduction heat gains through the building's envelope, called sol-air gains.



4.10 and 4.11

Solar roses from Central Park in New York City show the average daily amount of solar energy on each vertical segment of a cylinder. Since solar angles are symmetrical about the solstices, each season was centered on an equinox or solstice. The lower images show radiation on a horizontal surface for each hour and day of the year from the same weather file.

Source: Autodesk's Ecotect output. Courtesy of Callison.

- Terrain that faces the sun's path may receive many times more solar irradiation than slopes facing gently away from it.
- Peak cooling loads are often defined as days with no clouds and peak solar irradiation, though many other factors can affect peak loads.
- Peak heating loads are often defined as days with full cloud cover and no direct solar gain.
- Cloud cover is the defining variable in daylighting design. A completely overcast sky is ideal for daylighting, since light is more evenly spread over the sky dome with less chance of direct or reflected glare from the sun, as discussed in Chapter 8.

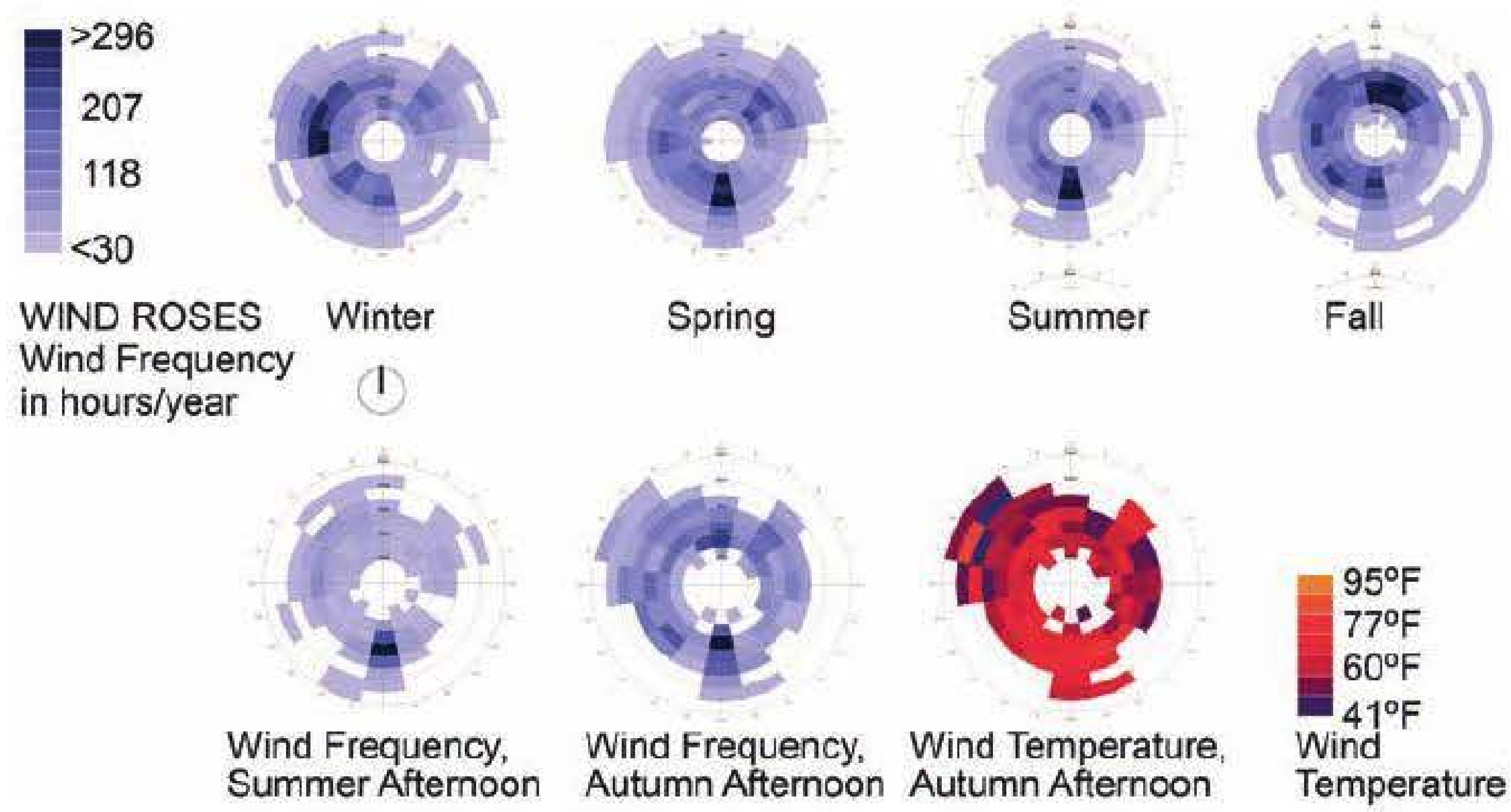
Micro-climate factors include:

- Clouds and fog often form near water bodies; several miles inland, conditions are generally less cloudy and foggy.
- Low clouds are driven by micro-climate wind effects of terrain near the Earth's surface, though above several hundred yards they are mostly driven by non-terrestrial forces.
- When the sun's ultraviolet rays hit pollution from vehicle combustion exhaust and industrial processes, smog is created. Smog tends to be worse in the summer, especially when it is contained by mountains such as in Los Angeles or Mexico City.

WIND

Wind may be channeled through urban canyons into uncomfortable high-velocity wind and swirls, while the right design can channel a breeze's cooling effects through a building to reduce or eliminate a mechanical cooling system. Wind is caused when areas with lower air densities (barometric pressure) pull air from adjacent areas with higher densities. Wind is described in terms of speed and direction and most often displayed as a wind rose, showing the frequency with which each combination of speed and direction occurs.

Wind speed increases at increasing elevations above the surrounding terrain according to a function called the wind gradient. Wind speeds at airports are typically measured at 33' above the ground, so wind speeds from weather files will over-predict wind speeds for ground-level buildings and under-predict for taller buildings. Generally, a few hundred yards above the surface of the Earth (above the boundary layer), wind flows at much higher speeds, without interacting significantly with the terrain below. These wind patterns circulate warm and cold air across the globe.



4.12

Wind roses graphically display wind data from a Manhattan TMY3 file with increasing frequency shown in a darker color; increasing wind speed is shown as a distance from the center. From these charts, summer winds can be read as typically coming from the south, while winter winds are generally from the west. Wind roses can be looked at in much greater detail as well: during summer afternoons when natural ventilation is most appropriate, breezes are consistently from due south. An outdoor restaurant designed for autumn use has another reason to face south, since the breezes from the south are comfortable temperature-wise as well, whereas colder winds are coming from northeast and northwest.

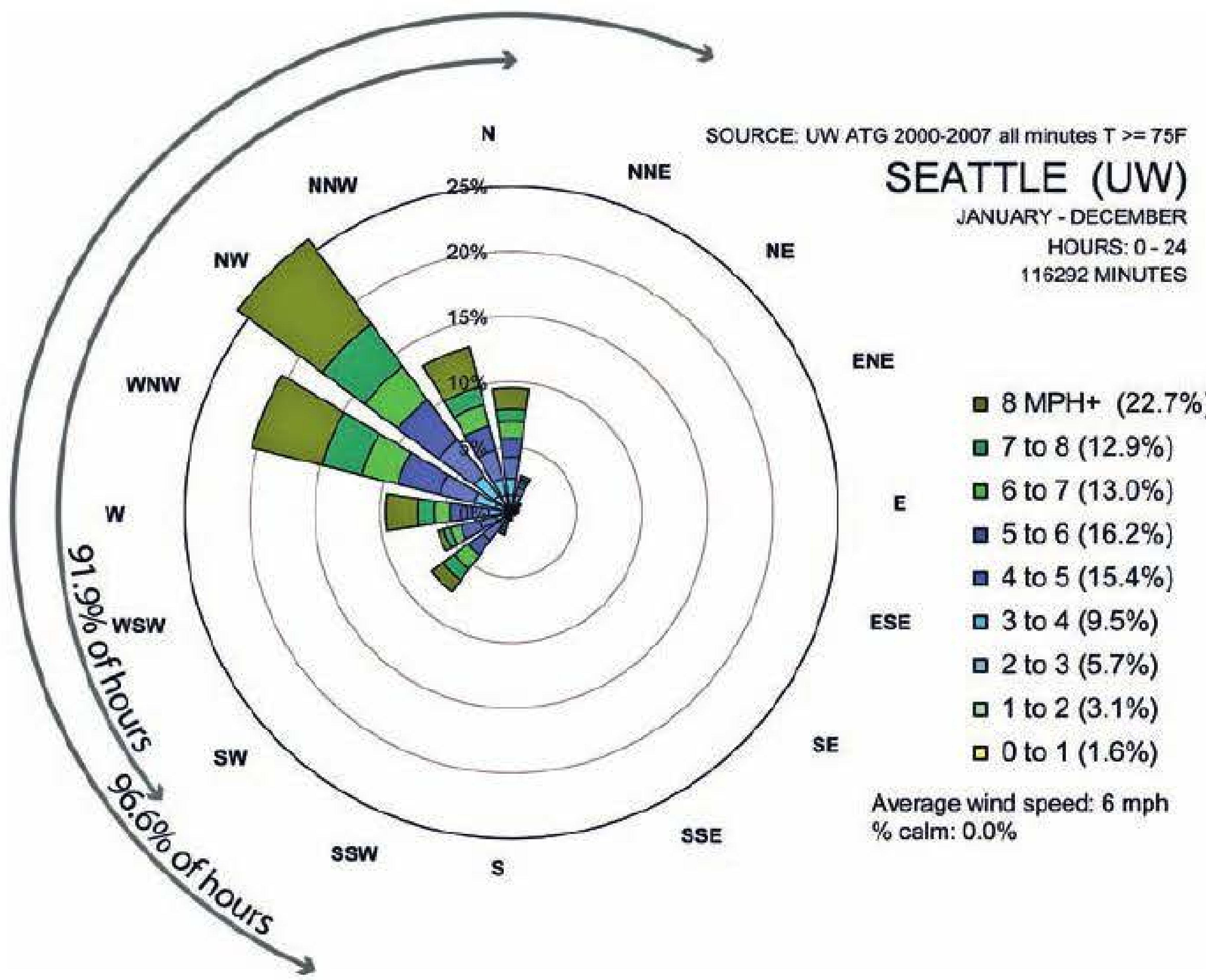
Source: Output from Autodesk's Weather Tool. Courtesy of Callison.

Buildings, trees, hills and mountains shape the wind near the ground, increasing wind speed or causing eddies as it flows around them and creating myriad localized wind conditions. For example, cold winter winds may come from the north generally in Seattle, but these same winds may come from the northeast or northwest on a given site due to local terrain or nearby buildings.

Wind studies on buildings may use physical models in wind chambers, computer-based Computational Fluid Dynamics (CFD) software for point-in-time analysis, or bulk airflow analysis by hand or as part of hourly energy modeling; these methods are covered in Chapter 9.

Some ways that wind is used in building design and simulation are:

- Wind can be used as part of a natural ventilation strategy that provides fresh air and/or cooling. This requires a wind-responsive building orientation, shape, interior volume, and operability at each floor.
- High winds can cause air leakage (infiltration), increasing energy loads; for this reason, blower door tests (used to verify infiltration levels) cannot be performed when outdoor wind levels are above a certain threshold.
- Wind scoops at the rooftop can be designed to draw fresh air in and exhaust stale air, and can be part of an evaporative cooling system.
- TMY file months are not selected based on typical wind direction, and contain a low weighting for wind speed, so wind energy simulations should be based on other sources.
- Wind power integrated into buildings is more of a gesture than an effective power generation strategy.
- Naturally ventilated spaces require a well-thought-out façade design to control wind gusts that would ruffle papers and create discomfort.
- Outdoor spaces in urban or windy areas can use simulations to anticipate and avoid eddies, downdrafts, or updrafts at entries and plazas.



4.13

Local wind data has been compiled to show frequency, direction, and speed during those hours of the year where the outdoor air temperature is above 75°F. This data helped determine that wind direction and speed were consistent enough to provide natural ventilation cooling for the offices at the University of Washington Molecular Engineering & Sciences Facility.

Source: Courtesy of ZGF Architects.

- Wind chill is an experiential metric that estimates how much additional heat a person loses when exposed to wind in addition to cold air temperatures. At 10°F, a 33 ft/s wind speed will cool off a human roughly equivalent to –13°F with no wind.

Micro-climate factors include:

- Buildings create nearby positive and negative pressures that can be used to draw air through a building. Computer-based wind simulations are used to test for the location and strength of these pressures.
- Wind data is taken from wide-open airports, so wind speeds and directions are likely to be different for low-rise buildings in urban contexts. These sites require simulation, research, or experience to anticipate effects.

PRECIPITATION AND STORMS

Our lives depend daily on fresh water, which is most often supplied by rain and melting snowpack. Precipitation determines the density of vegetation in each region, causes flooding in many parts of the world, and accompanies thunderstorms, hurricanes, and other storms. Some of the most important strategies for human well-being and sustainability depend on rainfall and water, but these are beyond the scope of this book.

Precipitation occurs when clouds or airborne humidity are cooled until they condense sufficiently for gravity to counteract buoyancy. Clouds and airborne humidity can be cooled by expansion while rising, when encountering a mass of cooler air or through other means. Precipitation is measured in inches of rain or snow; an inch of rain can be equivalent to between 3 to 20 inches of snow, depending on snow density.

Many areas experience localized weather events, including lightning strikes, seasonal dust storms, typhoons, hurricanes, high-speed wind gusts, and monsoons. The effects of these are not captured entirely by a weather file but may affect building design. For example, dust storms may reduce the amount of time each year that natural ventilation can be used. Searching for additional information is always important in analyzing an unfamiliar climate.

Some ways that precipitation is used in building design and simulation are:

- Since precipitation is generally colder than the air temperature near the ground and since water stores heat well, rainfall absorbs energy from a roof's surface before it drains away.
- Rain can ruin the effectiveness of green roofs' insulation value in cool, rainy seasons. Rain penetrates through the thin soil layer to cool the roof, and the soil moisture-holding capabilities later lose additional heat to evaporation.
- Deep, dry snow creates a thermal blanket, increasing the effective insulation value of a roof assembly.
- Snow creates a host of building science issues in cold climates that need to be carefully considered.

Micro-climate factors include:

- Precipitation increases on windward slopes and decreases on leeward slopes.
- Precipitation increases near water bodies due to higher local humidity levels.

CONCLUSION

The art of climate-responsive design was discarded by many architects in the twentieth century, due in part to being able to create indoor comfort with brute force using abundant fossil fuel energy. With the costs of fossil fuel energy use now known to be environmentally catastrophic, creating comfort within buildings requires a more sophisticated response to outdoor conditions.

Running and understanding simulations require comprehension of each of these climate factors, as well as how a given site may have a micro-climate different in some ways from the nearest weather file. From an analysis of the climate as part of a project kick-off, to the investigation of strategies through all design phases, low-energy buildings depend upon responding to each aspect of climate appropriately.

ADDITIONAL RESOURCES

Brown, G. Z. and DeKay, M. (2000) *Sun, Wind and Light,* Chichester: John Wiley & Sons, Ltd.

http://cliffmass.blogspot.com/

Olgyay, V. (1963) *Design with Climate: Bioclimatic Approach to Architectural Regionalism*, Princeton, NJ: Princeton University Press.

Users Manual for TMY3 Data Sets http://www.nrel.gov/docs/fy08osti/43156.pdf

Wilcox, S. and Marion, W. (2008) *Users Manual for TMY3 Data Sets, NREL/TP-581–43156,* April. Golden, CO: National Renewable Energy Laboratory.

4.1 CLIMATE ANALYSIS

Project type:
Eleven 24-story residential towers and one 14-story office tower

Location:
Mumbai, Marahastra, India

Design/modeling firm:
Callison

This climate analysis for a warm, tropical area considers solar irradiation, temperature, and wind direction and speed to determine site planning issues. Other climate analysis statistics were not as important for this site planning exercise.

Overview

At project kick-off, the design team analyzed the climate to determine optimum building orientations. The rule of thumb for tropical climates includes protecting east, west and roof façades from solar gain, with glazed areas concentrated on the south and north.

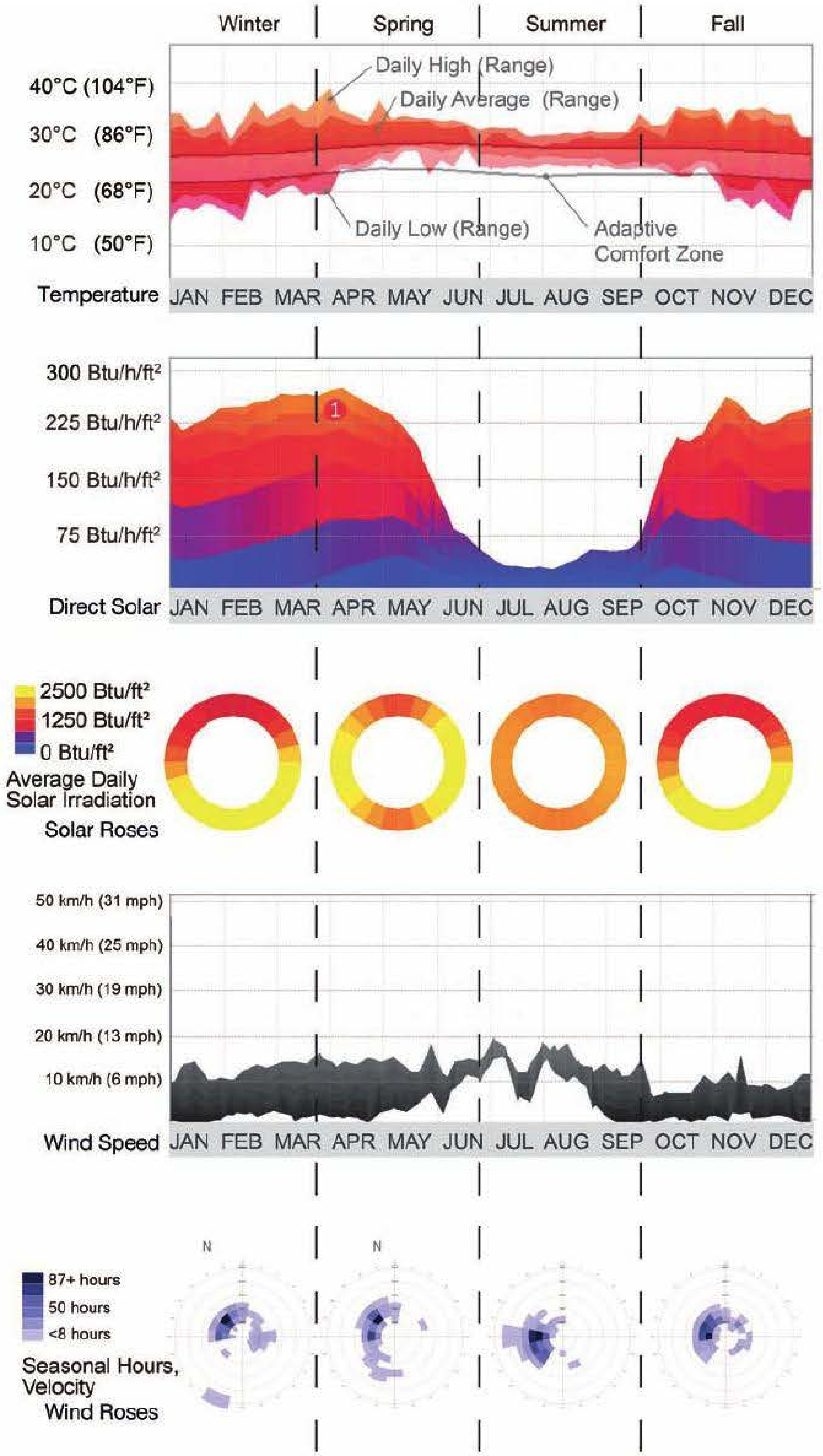
Residential towers in India are required to have light and operable windows in every room. Designs for mid-range condos typically include 3–6 units per elevator and stair core, with a single tower design often repeated and rotated around the site, making design for wind-driven cross-ventilation difficult.

Interpretation

Temperatures are above the indoor comfort range throughout the year—the adaptive comfort range is shown in light colors across the temperature profile. The hottest period is the Fall and Winter, and the coolest is the humid Summer monsoon. Solar gain throughout the year is very intense, except during the Summer monsoon. The solar roses show a southern bias during the hottest periods (Fall and Winter), an East–West bias in Spring, and nearly uniform irradiation during the monsoon, due to solar energy being diffused by clouds.

Afternoon winds that could aid in cooling tend to come from the west and northwest throughout the year. Orienting operable windows to these directions would allow through breezes to reduce dependence on mechanical cooling. The weather station is located only 3 miles southwest of the site, with no hills or terrain between them, so the team felt the climate data was reliable enough.

For these reasons, the team offered an initial design with the residential building having broad east and west façades. The eastern façade contained courtyards, so each unit would have light, ventilation, and through breezes. The western façade contained the majority of living spaces with balconies, providing deep shade structures for solar protection, large doors for through breezes, and a shading response to protect areas not already shaded.



4.14

Mumbai data.